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Comparison of Hybrid III and Cadaver Response using Force-Limited Belt Systems

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Abstract

This paper describes a series of frontal sled tests conducted using the Hybrid III dummy and three cadavers to evaluate the effectiveness of a force limited belt system in controlling occupant kinematics and mitigating injury. The tests used a 3 kN force limited retractor system with a belt pretensioner as primary restraint and a production driver side airbag as supplemental restraint. For the five dummy tests, the belt system performed well and all dummy test parameters were below injury thresholds detailed in FMVSS 208. In two of the three cadaver tests, however, the force limiting feature of the belt restraint was not effective due to problems with the pretensioning system. The cadavers in these tests experienced bilateral rib fractures, pneumothorax, and sternal fractures. The belt system did perform as designed in one cadaver test and resulted in significantly lower spinal acceleration, chest compressions, and overall injury severity. Analysis of the dummy and cadaver response data shows little difference between the surrogate responses to account for the why the belt system operated correctly in all dummy tests but did not perform as designed in two of the three cadaver tests. One possible explanation of the problems with the pretensioning system involves increased chest compliance of the cadavers relative to the dummies resulting in greater belt force relaxation during the early stages of belt loading.

Introduction

The three-point belt has proven to be an effective restraint system for mitigating occupant injuries in frontal crashes. The addition of load limiting capabilities to belt systems allows increased belt spool-out at predetermined force levels to produce lower accelerations of the occupant's chest and head as well as lower deformations and rates of compression for the thorax. Furthermore, occupant kinematics can be modified with the force limited belts to optimize load sharing by the belt and airbag restraint system and to load those anatomical complexes that are most able to withstand the restraint loads applied during a crash.

Previous experimental studies of force limited belt systems have been conducted by Kallieris et al. (1995) and Crandall et al. (1997). Kallieris et al. investigated the effectiveness of belt and airbag restraints using conventional and 4 kN force limited three-point belt systems. Sled tests were conducted at 48 km/h with the Hybrid III dummy and cadavers. Despite reduced belt loads with the force limited systems, Kallieris et al. found that the maximum chest deflection was roughly the same for conventional and 4 kN force limited belt but the deformation pattern was less localized for the force limited belt.

Crandall et al. used frontal sled tests to compare the performance of three driver restraint systems: conventional belt (CB), conventional belt with driver airbag (CB/AB), and nominal 2 kN force limited belt with driver airbag (FL/AB). Nine human cadaver and six dummy sled tests were conducted at 56 km/h. The FL/AB restraint system demonstrated significantly improved restraint effectiveness relative to the CB and CB/AB systems in terms of kinematic and kinetic response as well as injury data. Specifically, the FL/AB system produced the lowest chest compressions, V*C values, rates of compression, and changes in chest curvature for the cadaver response data. These results were supported by the reduction in injury frequency and severity for the force limited belt system relative to the CB and CB/AB systems.

The study presented in this paper is intended to expand the existing experimental data for force limited belt systems by testing cadavers and dummies restrained with a 3 kN belt system.

Methodology

Equipment - The tests were conducted using the sled system (Via Systems Model 713) at the University of Virginia's Automobile Safety Laboratory. The test buck utilized in this test series was an approximation of the passenger compartment of a mid-size vehicle. The test buck was outfitted with an energy-absorbing steering column set to yield at 2300 N. An adjustable knee bolster device was used to simulate the energy-absorbing characteristics of production knee bolster/dash assemblies while allowing a range of adjustment of position, angle, and energy-absorbing capability along with the ability to measure the forces involved. The seat was a production model bucket seat equipped with an anti-submarining pan integral with the bottom cushion frame. Seat position was adjusted to accommodate the range of anthropometries required for the cadavers. Positioning priority was given to maintaining a consistent chest to steering wheel hub distance for all occupants while providing realistic distances between the knees and bolster and the head and windshield.

High speed photographic data was recorded by servo-controlled 16mm high speed rotary prism movie cameras (either Photosonics 16mm-1B, or Hycam) arranged in stationary, off-board, or on-board positions. An offboard driver side camera was positioned to record a side view of the crash event for subsequent use in film analysis. All cameras were operated at a speed of 1,000 frames/sec. Phototargets were placed at the occupant's ankle, knee, hip (H-point for the dummy), elbow, and shoulder joints as well as the head center of gravity. Motion analysis of the high speed film was performed using a film motion analyzer (NAC Inc. model 160F) and motion analysis program (Concurrent Processing Inc. MAP software).

The airbag for this test series was a production driver airbag that had not been optimized for use with force limited belts. The seat belt utilized in the tests was a 3-point belt restraint that incorporated both a squib-activated pre-tensioning device and an energy absorbing retractor assembly. The application of a squib-generated force applied torsionally to the retractor spool in the direction of belt take-up pre-tensions the restraint system to a force level of approximately 1 kN prior to the onset of occupant translation. Detachment of the pretensioner cable is achieved through the application of load to the belt by the occupant which forces the pretensioner cable against a one-way spring-loaded knife edge. Thus, the cable is allowed to move freely over the knife edge during pretensioning but is cut when the cable travel direction is reversed from loading by the occupant during the crash event. A simple schematic of the system is shown in Figure 1.

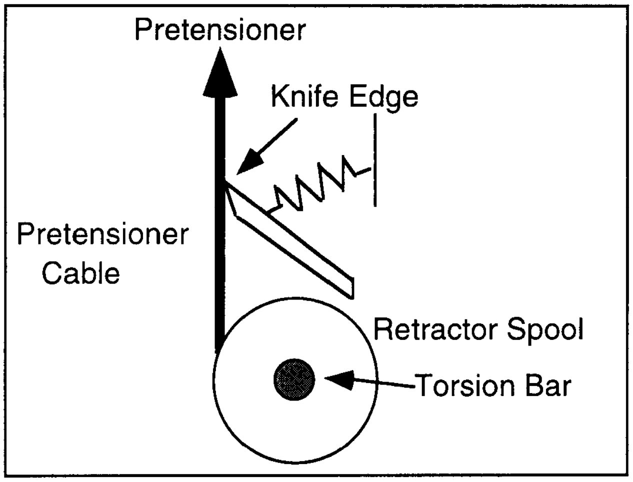

Figure 1. Simplified schematic of force limiting retractor with pretensioner.

Energy absorption by the retractor assembly was managed through a torsion bar between the web spool and the retractor lock mechanism. The belt restraint was a modified production retractor system in which the nominal force limit was reduced from 4 kN to 3 kN by decreasing the diameter of the torsion bar. Thus, the torsion bar was designed to yield under an applied belt load of 3 kN and to maintain this load during belt pay-out.

An approximate measurement of the maximum amount of belt webbing which was pulled out of the retractor assembly was taken by comparing the position of the webbing, relative to the retractor, before the launch and after the impact. For the measurements, a string was sewn to the belt webbing, at a location near the retractor when the belt was in position around the occupant. A small block of polystyrene foam was attached to the test fixture close to the retractor spool and in line with the vertical section of the belt between the retractor and the D-ring. The free end of the string was pushed through the foam block, using a needle. Immediately before the launch (after all occupant positioning procedures had been completed and after cadaver pulmonary pressurization had been initiated), the string was pulled taut and marked at the edge of the foam block. After the impact, before the occupant is disturbed, the string was marked again. The distance between the two marks was measured and recorded after the test. A redundant measure of belt spool-out was determined from film analysis of a phototarget attached to the belt webbing at the b-pillar.

<u>Surrogates</u> - The Hybrid III 50th percentile male dummy was used in baseline sled runs for all test conditions prior to testing of the three male cadavers (see Appendix A for dummy and cadaver anthropometry). Due to problems achieving a constant force level in previous tests with another force limiting belt system (Crandall et al., 1997), five dummy tests were conducted to ensure repeatable operation of the restraint system. For the

cadaver tests, three cadavers were obtained through the Virginia State Anatomical Board with explicit permission given by the family to conduct biomechanics research. All tests were approved by the Human Use Review Panel (HURP) of the National Highway Traffic Safety Administration (NHTSA) and all personnel involved in cadaver testing read and signed Ethical Treatment of Human Surrogate Forms supplied by the HURP. Screening of blood for Hepatitis A, B, C, and HIV was conducted with each cadaver prior to acceptance into the research program. The cadavers were tested either in the fresh condition or preserved using freezing or a custom embalming technique (Crandall et al., 1991). To simulate living conditions, pulmonary and cardiovascular pressurization was performed prior to testing.

Test Conditions - The frontal sled tests were conducted with a nominal delta-V of 58 km/h. The peak deceleration of the buck was approximately 23 g's with a pulse duration of 100 ms. A summary of the test conditions for each surrogate is provided in Table 1.

Table 1. Sled test impact conditions and surrogate anthropometric data.

Test	Surrogate	Sled Delta-V (km/h)	Max. Sled Decel. (g's)	Sex	Age	Height (cm)	Mass (kg)
D-406	Hybrid III	59.7	24.3	Male	NA	173.0	78.2
D-407	Hybrid III	58.2	23.8	Male	NA	173.0	78.2
D-408	Hybrid III	58.2	23.5	Male	NA	173.0	78.2
D-409	Hybrid III	57.8	22.8	Male	NA	173.0	78.2
D-410	Hybrid III	57.2	22.5	Male	NA	173.0	78.2
C-411	Cadaver	57.5	22.4	Male	60	172.0	72.1
C-412	Cadaver	56.8	22.3	Male	70	177.5	90.7
C-413	Cadaver	57.2	21.5	Male	57	180.3	98.9

Instrumentation- Dynamic deformation data for the upper and lower thorax was determined using chestbands, non-invasive devices designed for the measurement of cross-sectional contours of the chest during an impact event (Eppinger, 1989). For the dummy tests, the chestbands were placed at the level of the second (upper band) and fifth (lower band) ribs. For the cadaver tests, the bands were adhered to the chest at the location of the fourth (upper band) and the eighth rib (lower band) to provide chest deformation measurements about the ribcage, specifically near the heart and liver. Static verification data and measurements were taken before the dynamic test event to validate static chestband contours.

Output from the chestbands consisted of local curvature data that was initially filtered to SAE CFC-1000. Chest deformation contours were derived from this processed data using a variant of the RBANDPC program developed by the Chi Associates. From this position data, local gauge and sternum velocity were obtained using a four point finite-difference approximation that was further filtered to SAE CFC-180.

The dummies were instrumented with a triaxial accelerometer (three Endevco Model 7264a) array at the chest and head center of gravity. A uniaxial accelerometer was also attached to the upper breast plate and the chest potentiometer (i.e., slider assembly) was used to record chest deformation data to supplemental the chestband data. For the cadaver tests, triaxial accelerometers (Endevco Model 7267) were mounted on the first thoracic vertebra, the second lumbar vertebra, and the pelvis. In addition, a uniaxial accelerometer (Endevco Model 7264a) was mounted on the body of the sternum. Each component of raw acceleration data was filtered to SAE CFC-60 prior to taking resultants.

Belt-tension load cells (Eaton Corp., Lebow Model 3419-3.5k) were mounted on the outboard shoulder and lap belts and on the inboard shoulder belt. Raw belt load data was processed by removing initial offsets and filtering to SAE CFC-180.

Electronic data was acquired at 10,000 samples/sec. using a DSP Technology Transient Acquisition and Processing System, model TRAQ-P. The data was collected using IMPAX, a DSP technology PC-based data acquisition program.

Injury Documentation - Pre-test radiography was conducted to identify any existing injuries or anomalies, to verify instrumentation mounting locations, and to provide a reference with which to compare post-test radiography. Following the tests, additional radiographs were taken and standard autopsy procedures were performed by a pathologist and autopsy specialist. Examinations of the cadaver's cardiovascular system, abdomen, viscera, brain, head and neck, spine, and other skeletal elements were performed. The breast plate was removed and the number and location of rib fractures was documented. Rib fracture distances were measured relative to the jugular notch and the mid-sagittal plane. Measurements relative to the mid-sagittal plane followed the contour of the rib to the location of fracture in a coronal plane. All injuries were coded according to the Abbreviated Injury Scale (AIS) and the maximum AIS value (MAIS) was recorded.

Results

Examination of the kinematic and kinetic data from the restraint testing suggests that the force limited belts were effective in producing low occupant response parameters and minimizing injury when the system operated correctly.

Film Analysis - Motion analysis of the high speed film was conducted to determine occupant kinematics (Table 2) relative to initial occupant positioning in the buck. Initial chest to steering wheel (CS) and head to windshield (HW) distances are provided for reference. The dummy tests show repeatable positioning with all initial measurements reproduced in each test to within 2 cm. Increased variability in initial position measurements with the cadavers is largely due to anthropometric variability.

The film showed that test D-406 experienced failure of the belt attachment at the D-ring mount resulting in greater occupant excursion. Other than test D-406, however, all dummy tests generated similar head, shoulder, and hip excursions. Examination of the high speed film indicated less shoulder excursion in tests C-411 and C-413 and it appeared that the shoulder belt allowed less pay-out in these tests. This observation was subsequently verified by examining the belt pay-out measurements and the torsion bar deformation following the tests.

Analysis of the high speed film also showed differences in occupant rotational kinematics based on the load limiting of the belts. For the cadaver tests, C-411 experienced 31 degrees of torso rotation while C-413 exhibited 22 degrees. Both of these tests showed less torso rotation than test C-412 (35 degrees) in which the force limiting feature of the belt worked. For these tests, the degree of torso rotation was inversely correlated with the maximum belt load. Similarly, most of the dummy tests exhibited higher torso rotations but there was considerable test to test variability.

Table 2. Film analysis results of maximum kinematic values for the occupant.

Test	CS (cm)	HW (cm)	Head Excursion (cm)	Head Velocity (m/s)	Shoulder Excursion (cm)	Hip Excursion (cm)	Torso Rotation (°)
D-406	29.5	47.4	54.6	7.96	52.7	22.4	49.5
D-407	28.5	45.9	40.4	7.33	39.4	15.5	37.7
D-408	29.5	49.0	38.8	7.40	36.1	14.2	33.5
D-409	30.1	48.6	40.4	7.12	38.5	12.9	42.1
D-410	27.6	48.7	38.1	6.34	37.6	14.1	31.5
C-411	31.5	55.0	37.4	7.67	33.0	13.0	30.9
C-412	30.8	42.0	49.6	8.29	42.8	13.5	35.4
C-413	29.8	48.5	46.6	8.41	31.2	11.8	22.1

Post-test Inspection - Following each test, the seat belt retractors were disassembled to visualize deformation of the torsion bar and cutting of the pretensioning cable. Table 3 illustrates that the pretensioning cable was completely cut in only test D-407 and partially cut in all other tests except tests C-411 and C-413. Pretensioning of the belt system is achieved by pyrotechnically preloading the belt to a level of 1 kN. Following this preload, the cable attached to the retractor should be forced against a knife edge under the tension of belt loading by the occupant. Cutting of the pretensioning cable should allow the belt forces to be controlled initially by the properties of the belt. Subsequently, the retractor's torsion bar yields after the belt loads reach 3 kN. For the tests in which the pretensioner cable was not cut or was only partially cut, however, there existed an additional load path through the cable.

In addition to the post-test inspection of the retractors, belt pay-out was evaluated from film analysis and from direct measurements using the string and foam block. As expected, table 3 verifies that cadaver tests in which the pretensioner cable was not cut experienced lower belt pay-outs than those tests in which it was partially cut. Dummy tests show similar results when comparing the partially cut tests to test D-407 in which the pretensioner cable was cut cleanly.

Table 3. 3kN force limited belt performance summary.

Test	Pretensioner CableSeparation?			Pretensioner Spool-in		Belt Pay-out ①	
	Yes		No	Max. Value (cm)	Time (ms)	Max. Value (cm)	Time
	Cut Cleanly	Cut Partially					
D-406		✓		--	--	--	--
D-407	✓			7.9	15.7	25.4	99.3
D-408		✓		7.7	17.2	22.2	108.9
D-409		✓		4.1	15.7	21.8	98.4
D-410		✓		4.1	19.7	22.9	93.4
C-411			✓	6.2	15.7	22.6	93.9
C-412		✓		5.9	17.7	26.9	102.4
C-413			✓	6.4	15.7	22.4	93.9

① Values represent total belt spool-out, i.e. beginning at spooled-in belt position

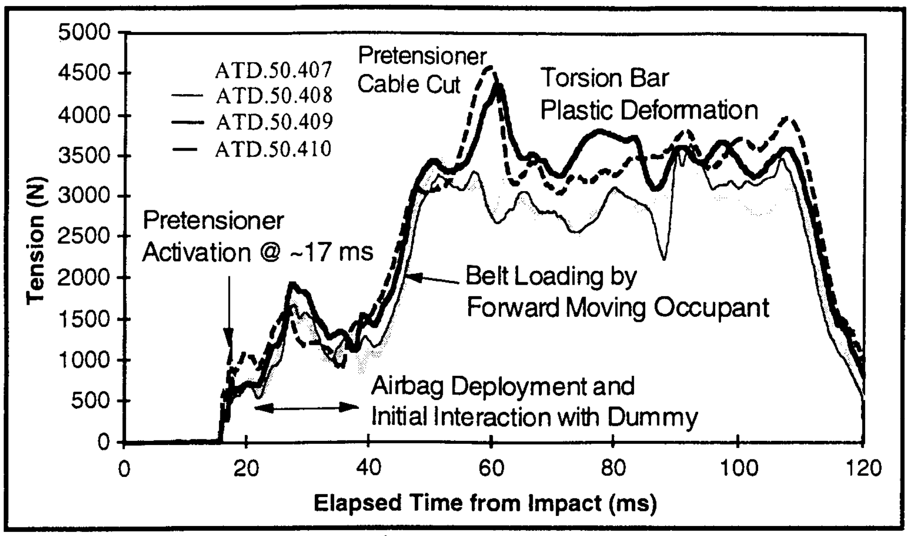

Figure 2. Shoulder belt force-time histories for dummy tests.

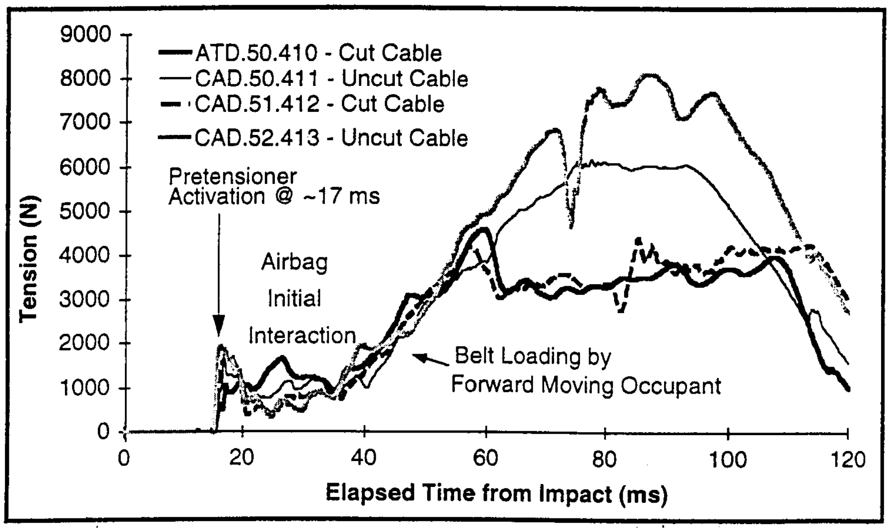

Figure 3. Shoulder belt forces for cadaver tests relative to a typical dummy test.

It is evident from Figures 2 and 3 that the should belt forces were significantly reduced when the system operated as designed. Comparison of the maximum belt forces (Table 5) shows that when the system performed as designed there appears to be no significant differences in the peak belt forces between dummy and cadaver tests.

Table 5. Summary of restraint parameters and responses

Test	Upper Shoulder Belt Load (kN)	Lower Shoulder Belt Load (kN)	Outboard Lap Belt Load (kN)
D-406	NA	2590	5110
D-407	3480	3940	6830
D-408	3650	3900	6200
D-409	4380	3700	6450
D-410	4590	3570	6460
C-411	6150	2750	4030
C-412	4380	2650	4560
C-413	8120	4280	4690

The chestband data provided a comparison of sternal deformations and rates of compression for the three restraint systems. Maximum chest compressions and the sternal Viscous Criteria (V*C) (Lau and Viano, 1986) were calculated from the chestband data (Table 5). Injury assessment reference values (IARV) were taken to be 50 mm of sternal compression and 1.0 m/s for the Viscous Criteria for a 50[th] percentile male Hybrid III (Mertz, 1993). Using these IARV, it is evident that when the force limiting system operated as designed all values were below the threshold values. In the cases where the system did not limit the forces, however, the cadaver chest compressions exceeded the IARV.

Table 6. Maximum sternal deformations (Def) and Viscous Criteria (VC)

	Maximum Sternal Deformation				Maximum Sternal Viscous Criteria			
	Upper Chestband		Lower Chestband		Upper Chestband		Lower Chestband	
Test	Def. (mm)	Time (ms)	Def. (mm)	Time (ms)	VC (m/s)	Time (ms)	VC (m/s)	Time (ms)
D-410	43	60.8	25	105.9	0.28	25.8	0.08	57.2
C-411	72	96.2	30	66.6	0.63	82.9	0.14	30.7
C-412	48	118.9	9.0	45.2	0.23	102.8	0.15	81.7
C-413	100	110.2	13	107.5	0.72	98.4	0.04	78.9

The chest compression-time histories were examined to see if any differences existed between those cases in which the pretensioning cable was cut and those in which it wasn't cut (Figure 4). A hypothesis was that the belt may have been positioned differently on the chest for the two cases such that forces on the belt may load either a more rigid structure (e.g., the shoulder complex) or a more compliant structure (the anterior chest). Within the variation of the data, no trends could be observed and chest compressions were similar up until the point at which the torsion bar began to yield in tests D-410 and C-412 .

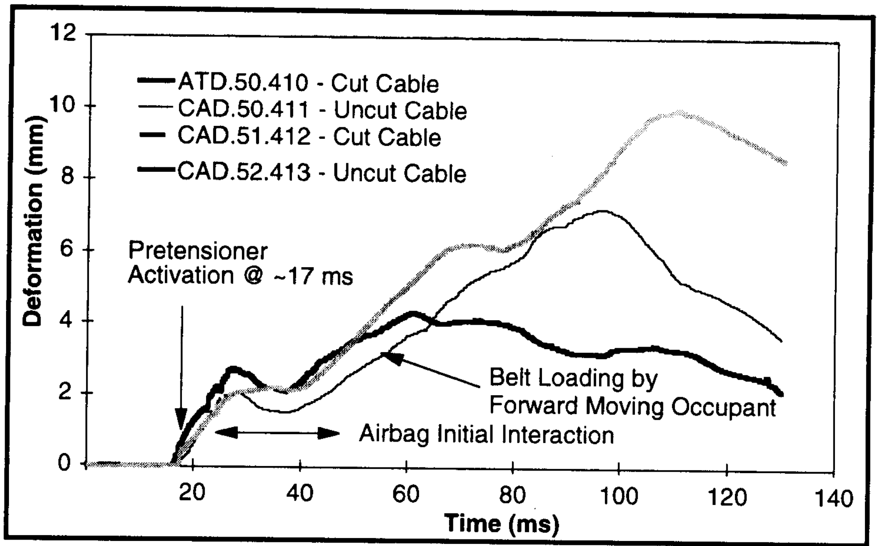

Figure 4. Chest compression-time histories.

In accordance with the belt load and chestband data, spinal accelerations at the T1 vertebrae were also greater for the two cadaver tests in which the belt system did not perform properly (59.8 g's to 82.8 g's) relative to the test in which force limiting occurred in the retractor (44.8 g's).

Injury Information - No head or neck injuries were identified in any of the cadaver tests. The most frequent thoracic injuries were rib and sternal fractures (Table 7). If a rib sustained multiple fractures, subscript notation was used in Table 7 to denote the number of fractures for a particular rib. The location of the rib and sternal fractures roughly coincide with the loading path of the belt onto the occupant's chest. An attempt at correlating the location of these fractures with either the location of maximum chestband curvature or deformation was unsuccessful. The most frequently fractured ribs were numbers 3,4, and 5 on both the right and left side.

The average number of rib fractures was not significantly greater for those cases in which the belt did not limit the forces. However, pneumothorax was identified in both tests in which the belt forces exceeded the limiting value, tests C-411 and C-413, while it was not evident in test C-412. Since the AIS values were primarily determined by the number of rib fractures and the presence of a pneumothorax, tests C-411 and C-413 had the highest AIS scores.

Table 7. Injury summary table

Test	Left Ribs Fractured	Right Ribs Fractured	Sternal Fracture	Clavicle Fracture	MAIS	Other Injuries
C-411	$3^2,4^2,5^2,6^2$,7,8	1,3,$4^2,5^2$,6,7,8	yes	no	5	pneumothorax
C-412	2,3,4,5^2,6,7	2,3, 4,5^2,6,7^3	no	yes	4	none
C-413	2, 3, 4, 5, 7	2,3, 4^2, 5	yes	yes	5	pneumothorax

Discussion and Conclusions

The force limited seat belt retractor assemblies utilized in the test series did not perform consistently in all tests. Most significantly, post-test examinations of the retractors revealed various degrees of pretensioner cable separation which resulted in major inconsistencies in the amount of belt spool-out achieved during the constant-force phase of the event.

When the belts performed as designed, the occupant kinematics were effectively controlled by the airbag, force-limited belt, and knee bolster restraint system. In the dummy test, the force limited belt (3 kN) provided significant excursion of the occupant but did not permit head contact with any interior vehicle components other than the airbag. In the cadaver tests, the belt system did not function as intended in tests C-411 and C-413 due to problems with the pretensioning system. Post-test examination of the force limiting system indicated that the pre-tensioning cable had not separated from the force-limiting torsion bar. This resulted in the belt applying loads to the cable rather than the torsion bar and resulted in no force limiting of the belt-retractor system.

Similar to the dummy tests, C-412 showed considerable excursion of the occupant with 26.9 cm of belt spool-out. Examination of the high-speed film shows apparent head contact with the windshield and header. The increased excursion over conventional belt systems may have been exacerbated by the size of the occupant (178 cm, 90.7 kg) which is slightly larger than the Hybrid III 50th percentile dummy (173 cm, 84.8 kg instrumented).

The belt system in test C-413 performed similarly to the belt in test C-411. Examination of the belt force-time histories suggests differences in the dummy and cadaver loading of the belt system following pretensioning that may explain why the belt performed well in the dummy tests but not the cadaver tests. Specifically, the dummies appear to maintain a load on the belt while the load relaxes considerably in the cadaver tests (Figures 1 and 2). This behavior may have contributed to failure of the retractor knife edge to cleave the pretensioning cable. When the retractor was originally developed, it was specified that forward displacement of the occupant should be limited even without the pretensioner being fired. This led to a design in which the force limiting function is engaged only if the pretensioner is fired. The force limiter function is then engaged as long as the shoulder belt force is above a critical level. If the force falls below this level, a spring loaded pawl disengages the force limiting function.

The time histories of the cadaver and dummy tests were provided to the belt manufacturer. Their analysis of the upper shoulder belt force-time histories noted a difference between dummy and cadaver response. After the shoulder belt was initially loaded, the force dropped to approximately a 1 kN value in the dummy tests while the force dropped to approximately half that level in the cadaver tests. The belt force at the retractor was likely even lower due to friction forces over the D-ring surface. At this low belt force level, the force limiting function could be disengaged due to the spring acting on the pawl mentioned previously.

Since the testing presented in this paper, the force limiting function of the retractor has now been modified such that it is always engaged and cannot be disengaged. It is interesting to note, however, that neither the manufacturer nor we observed failure of the pretensioning system in dummy tests. This may suggest that differences between the response of the dummy and cadaver thoraxes may be sufficiently significant to alter restraint designs. Some of the response difference, however, may be attributed to the lack of muscle tone in the cadavers while the Hybrid III dummy chest stiffness has been based on tensed volunteers.

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Appendix A: Surrogate Anthropometry and Information

OCCUPANT SUMMARY				
TEST NUMBER	**ATD.50.406-ATD.50.410**	**CAD.50.411**	**CAD.51.412**	**CAD.52.413**
GENERAL INFORMATION				
Type	Hybrid III	Cadaver	Cadaver	Cadaver
Number	910	96-EM-57	96-EM-60	95-EM-53
Gender	Male	Male	Male	Male
Age at Death	Not Applicable	60	70	57
Date of Death		3/21/96	5/23/96	6/10/95
Cause of Death		Coronary Insufficiency	Myocardial Insufficiency	Cerebral Edema
Anomalies		None	None	None
Preservation Method		Embalmed	Embalmed	Embalmed
ANTHROPOMETRY				
Height (cm)	173.0	172.0	177.5	180.3
Weight (kg)	84.8	72.1	90.7	98.9
RADIOLOGY				
Pre-Test Injuries	Not Applicable	None	None	None
PRESSURIZATION METHOD				
Pulmonary	Not Applicable	Yes	Yes	Yes
Cardiovascular		Yes	Yes	Yes

DISCUSSION

PAPER: **Comparison of Hybrid III and Cadaver Responses Using Force Limiting Belt Systems**

PRESENTER: Jeff Crandall, University of Virginia

QUESTION: Hugo Mellander, Traffic Safety Research & Engineering AB, Sweden
Was this a driver environment?

ANSWER: Yes, this was a driver environment; driver's airbag and belt system for the driver.

Q: When we go into these force limiting belt systems, I wonder how robust these systems will be. If you go into higher velocity impact, what will happen? You will probably bottom out the airbag and go into contact with the steering wheel. I wonder if you have thought about this. We may be adjusting our systems to function very well for a certain speed. If you go above that speed, you may perhaps be better off with a fairly stiff seat belt system. Have you thought about this?

A: Yes. This is a fairly severe test; 56 kilometers per hour. We were trying to address a number of computational studies looking at different size occupants that have concluded that these low end systems might yield an optimal response. I think these tests could lead you to have a multi-staged load limiting. In other words, if I had a certain amount of excursion, I could have load limiting at two kilonewtons. More, and I might go up to three kilonewtons or some other value. So, I think these levels are just an indication of what the potential reduction could be, rather than how you would implement this in the real world.

Q: Guy Nusholtz, Chrysler Corporation
It looked like your problem had to do with the pretensioner and the knife that was cutting it. This was not necessarily related to a load limiting phenomena, but to other factors. You haven't really gone through and tested the load limiting. It is possible, and this happens a lot, that you have a device which is designed in sort of an unstable way, and it works for only one very small condition. Small changes in the events, things that you can't really detect, show up as sometimes failing and sometimes not failing. As an example, we saw this with a Hybrid III with regard to the pelvis interaction. You could be developing a system and just a very small change in initial condition, would sometimes engage the pelvis with the chest and sometimes it wouldn't. You couldn't tell whether that was because the dummy was one millimeter back or because of some design change. So, it is possible that this particular system just isn't stable over a wide range of inputs, and that you may not be able to see any distinct difference in any of your data.

A: I hoped that you would have a better answer than that, Guy.

Q: It happens.

Q: Barry Myers, Duke University

I don't do much of this so it is easy to ask a real stupid question. You've got two failures in eight efforts to cut this belt. What is the probability of that occurring in three tests of eight? Essentially you have a twenty-five percent probability of an event occurring and you've got it partitioned into three tests. The probability of that is non-zero, so I wonder if this thing just isn't that reliable a system and you're just unlucky with your cadavers.

Q: That could be. We tried to run the five tests initially so that when we went to the cadavers, a very expensive and limited resource, we wouldn't have that problem. To answer that, though, this is a production pretensioning system in which they have run presumably hundreds and hundreds of tests. We called the manufacturer of this system, and they have never seen this in their laboratory testing. That is the only way I can answer it. They said they've never seen it.

Q: Gopal Narwani, Takata

If I heard correctly, you said that this production system was a four kilonewton system which was modified by your request to three kilonewtons. So, I don't think that you should refer to that as a production system. Instead, it is a modified production system which may have not undergone enough developmental testing before it was supplied to you.

A: The only problem with that argument is that the pretensioning system was unmodified. That is exactly the same as in the production system. The difference between the four kilonewton and three kilonewton system is the diameter of the torsion bar, so just one particular pin was replaced and all the complimentary components were left untouched and the components in which they failed were untouched. I don't think we are going to try this again with the four kilonewton systems but if anyone does have any ideas afterwards, I have some video if anyone wants to look at it in more detail. Maybe Guy can help us out. I'd appreciate your ideas.